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CRYSTALLINE SILICATES AS A PROBE OF DISK FORMATION HISTORY

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ABSTRACT

We present a new perspective on the crystallinity of dust in protoplanetary disks. The dominant crystallization by thermal annealing happens in the very early phases of disk formation and evolution. Both the disk properties and the level of crystallinity are thereby directly linked to the properties of the molecular cloud core from which the star+disk system was formed. We show that, under the assumption of single star formation, rapidly rotating clouds produce disks which, after the main infall phase (i.e. in the optically revealed class II phase), are rather massive and have a high accretion rate but low crystallinity. Slowly rotating clouds, on the other hand, produce less massive disks with lower accretion rate, but high levels of crystallinity. Cloud fragmentation and the formation of multiple stars complicates the problem and necessitates further study. The underlying physics of the model is insufficiently understood to provide the precise relationship between crystallinity, disk mass and accretion rate. But the fact that with 'standard' input physics the model produces disks which, in comparison to observations, appear to have *either* too high levels of crystallinity *or* too high disk masses, demonstrates that the comparison of these models to observations can place strong contraints on the disk physics. The question to ask is not why some sources are so crystalline, but why some other sources have such a *low* level of crystallinity.

Subject headings: accretion disks — (ISM:) dust — (stars:) planetary systems: formation, protoplanetary disks

1. INTRODUCTION

One of the major discoveries achieved with infrared spectroscopic studies of Herbig Ae/Be stars and classical T Tauri stars is that a significant percentage of the dust in their circumstellar disks is of crystalline form (e.g. Bouwman et al. 2001; van Boekel et al. 2005; Apai et al. 2005). Also in our own solar system there is evidence, from observations of comets, that the dust of the primordial solar nebula was partly crystalline (Wooden et al. 1999). This poses an interesting puzzle because the dust inherited from the interstellar medium must have been amorphous (Kemper et al. 2004; 2005) and hence the crystallization must have taken place *within* the disk. Since silicate dust crystallizes only when heated to relatively high temperatures ($\gtrsim$ 800 K), the discovery of these crystals proved that the dust in such disks is (or has been) subject to processes involving high temperatures.

The very inner regions of protoplanetary disks (i.e. inward of the 'crystallization radius' which is about 0.1 AU for a T Tauri star and 0.7 AU for a Herbig star) are warm enough to thermally anneal the dust, and thus produce crystalline silicates like enstatite and forsterite. But the presence of crystalline dust in Solar System comets proves that processed dust also existed beyond the snow line where comets formed, well outside the crystallization radius (e.g. Wooden et al. 1999; Min et al. 2005). Similarly, the infrared spectra of T Tauri and Herbig disks show that crystalline silicates often exist out to radii as cool as 150 K. And by directly spatially resolving the disk down to 2 AU with interferometric 10 μm spectroscopy it has been shown that for many sources the outer cooler disk regions clearly contain crystalline dust (van Boekel et al. 2004), though a smaller fraction than in the inner disk regions.

Currently the most favored theory involves radial mixing (Gail 2001; 2002; Wehrstedt & Gail 2002; Bockelée-Morvan et al. 2002, based on earlier ideas by Morfill & Voelk 1984). Even though the main accretion stream in a disk points inward toward the star, the turbulent mixing within the disk can transfer at least a small amount of the thermally processed dust grains to larger radii. This typically results in decrease of crystalline silicate abundance with radius beyond the point where the temperature drops below the annealing temperature. However, this decline is slow enough that still a measureable quantity of crystalline silicates exists at radii where the 10 μm silicate feature is produced in protoplanetary disks, and where comets were formed in the protosolar nebula (Bockelée-Morvan et al. 2002). Whether or not thermal annealing and radial mixing alone are sufficient to explain the levels of crystallinity typically observed is debated. A possibility to enhance the outward transport of crystalline silicates was recently discussed by Keller & Gail (2004), who have shown that accretion in the inner disk regions is not always inward: While the surface

layers of a disk tend to accrete inward, the midplane of the disk moves outward. Any thermally processed grains may be transported very efficiently outward with this mechanism. Another possibility is the outward transportation of dust via wind (Shu et al. 1996).

In this Letter we wish to revisit the radial mixing theory from a new perspective. Instead of assuming a steady disk, or starting from a given disk structure, we take a step back and start from the collapse of the rotating prestellar cloud core. We assume that the collapse of such a core leads to the formation of a *single* star and a disk, even though this may not be the dominant mode of star formation. The properties and viscous evolution of this disk are strongly influenced by the rotation rate of the original cloud core (Nakamoto & Nakagawa 1994; Hueso & Guillot 2005). Rapidly rotating clouds deposit their mass onto the disk at large stellocentric radii, leading to the slower evolution of a more massive disk than if the cloud were rotating slowly. Slowly rotating clouds deposit most material close to the star where it will be strongly heated and then push outwards by viscous spreading, influencing the thermal history of material found in the outer disk (Fig. 4). Nakamoto & Nakagawa (1994) and Hueso & Guillot (2005) have modeled the formation and viscous evolution of protoplanetary disks using vertically integrated time-dependent viscous disk models. Here we follow a similar approach but along with the disk evolution we also passively evolve a dust population, including a simple treatment of crystallization and radial mixing.

In this Letter we only demonstrate the principle and present first results. In a follow-up paper we will describe the model in detail, explore the parameter space, discuss all the physical uncertainties and caveats, and compare the results to observational trends.

2. BRIEF DESCRIPTION OF THE MODEL

We start our simulations with a core with temperature $T_{\rm bg}$ (Kelvin), mass M (gram), and solid-body rotation rate Ω (radian/second). For the sake of simplicity we assume the core to be a singular isothermal sphere, required to apply the Shu collapse model. Here the collapse is triggered by an expansion wave propagating outward from the center with the sound speed $c_s \equiv \sqrt{kT_{\rm bg}/\mu m_p}$, initiating the collapse of every mass shell of the core it passes through. The infall rate is constant: $\dot{M}_{\rm infall} = 0.975\ c_s^3/G$, which for our choice of temperature, $T_{\rm bg} = 15\,$K, amounts to $\dot{M}_{\rm infall} = 3\times10^{-6} M_\odot$/year. For a cloud with a rotation rate Ω all the mass will fall onto the equatorial plane *inward* of the centrifugal radius $R_{\rm centr} \equiv \Omega^2 R^4_{\rm core}/GM_{\rm core}$, where the radius of the core is $R_{\rm core} = GM_{\rm core}/2c_s^2$. The way the infalling material is distributed over the disk is described by Hueso & Guillot (2005).

The disk is described by the surface density Σ as a function of the radius R. It obeys the equation:

$$\frac{\partial\Sigma}{\partial t} + \frac{1}{R}\frac{\partial R\Sigma v_R}{\partial R} = S\,, \qquad (1)$$

where S is the source function due to infalling matter onto the disk. The azimuthal momentum equation yields an expression for the radial velocity of the gas v_R:

$$v_R = -\frac{3}{\Sigma\sqrt{R}}\frac{\partial}{\partial R}\left(\Sigma\nu\sqrt{R}\right)\,, \qquad (2)$$

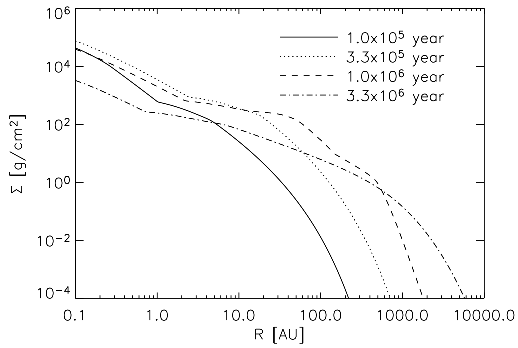

FIG. 1.— Surface density as a function of radius in the disk, for different times after the onset of collapse of the parent cloud.

where ν is the viscosity coefficient, given by $\nu \equiv \alpha kT_m/\mu m_p\Omega_K$. Here α is the parameter of viscosity (Shakura & Sunyaev 1973), which we take to be a global parameter, T_m is the midplane temperature, and Ω_K is the Keplerian frequency. We also include an effective viscosity caused by gravitational instabilities in regions where the Toomre parameter drops below unity. The midplane temperature is determined by taking into account heating due to viscosity and irradiation by the central star.

The dust is passively transported along with the gas, but is subject to radial diffusion through turbulence and to crystallization in those regions for which $T_m \gtrsim 800$ K. We therefore transport two dust components: an amorphous one and a crystalline one, with surface densities Σ_1 and Σ_2, respectively. Crystallization transforms one into the other at a rate given by the Arrhenius formula $\nu\exp(-T_c/T_m)\ {\rm s}^{-1}$ with the lattice vibration frequency $\nu = 2\times10^{13}$ (Fabian et al. 2000) and $T_c = 38100$ K (table 3 of Bockeleé-Morvan et al. 2002). The radial mixing equation is:

$$\frac{\partial\Sigma_i}{\partial t} + \frac{1}{R}\frac{\partial R\Sigma_i v_R}{\partial R} = \frac{1}{R}\frac{\partial}{\partial R}\left[RD\Sigma\frac{\partial}{\partial R}\left(\frac{\Sigma_i}{\Sigma}\right)\right] + S_i \quad (3)$$

where $D \equiv \nu/P_t$ is the diffusion coefficient, P_t is a constant that follows from numerical simulations (Johansen & Klahr 2005; Carballido et al. 2005). The source term S_i accounts for the infall of new matter onto the disk (only feeding the amorphous component) and for the transformation of amorphous silicates into crystalline ones. We assume that the amorphous primordial dust survives the accretion shock on the surface of the disk.

3. RESULTS

As an example, we take a Herbig Ae/Be star with $M_* = 2.5 M_\odot$, $T_* = 10{,}000$ K, $L = 50\ L_\odot$. The initial cloud is assumed to be at 15 K, and its rotation rate is taken to be $\Omega = 1\times10^{-14}{\rm s}^{-1}$. We assume that the viscosity parameter is $\alpha = 0.01$ throughout the disk.

In Fig. 1 the surface density profile as a function of radius is shown at various epochs after the onset of collapse of the parent cloud. In this example the centrifugal radius was located at 180 AU, i.e. all the matter from the infalling cloud fell within 180 AU from the star onto the disk. Viscous friction then causes much of the mass to accrete inward onto the star, while pushing a smaller fraction of the matter out to very large radii in order to absorb the angular momentum of the inward moving matter.

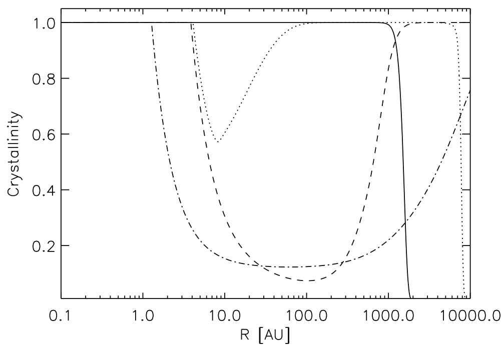

FIG. 2.— Abundance of crystalline silicates as a function of radius, for the same times as in Fig. 1.

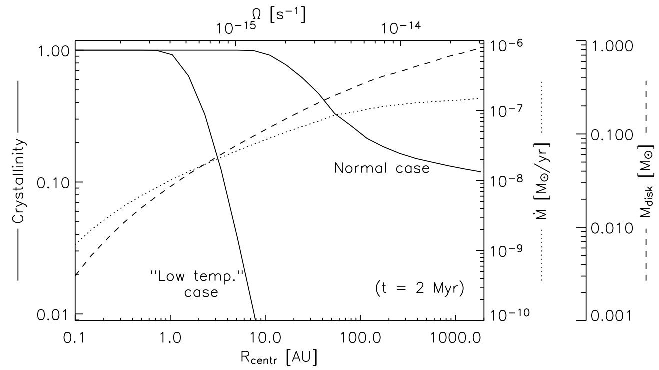

FIG. 3.— A number of disk properties plotted as a function of cloud rotation rate Ω, or equivalently as a function of the centrifugal radius $R_{\rm centr}$. The latter is the fundamental variable relevant for the disk evolution, but with the simple cloud collapse model it translates in Ω. The following quantities are plotted: the crystallinity at 10 AU (i.e. abundance of crystalline silicates: black solid curves), the mass accretion rate at the inner edge of the disk (dotted curve), and the disk mass (dashed curve), all measured at 2 Myr after onset of collapse, for the model parameters described in the text. The top black curve is for the model with the "standard" input physics. The bottom black curve is for the model in which the most optimistically low midplane temperature estimate is used, and in which the radial mixing efficiency is reduced by a factor of 10 (see text).

In the initial phases of the infall ($t \ll 10^6$ year), however, the centrifugal radius of the infalling matter was smaller than 180 AU because the inner parts of the rigidly rotating cloud had a lower specific angular momentum. Therefore, in the early phases of the collapse most of the matter falls much closer to the star than in the later stages. In these inner regions the disk becomes so warm due to accretion that all the dust crystallizes or evaporates. As some of this matter is pushed out for reasons of angular momentum conservations (not necessarily radial mixing), this matter cools off and, if the dust was evaporated initially, it recondenses directly into crystalline form. Hence, the spreading disk is transferring crystalline matter from the inner disk to large radii, causing initially the disk to be fully crystalline, as shown in Fig. 2.

In the later stages of the infall ($\sim 5\times10^5\cdots10^6$ years), the collapse wave reaches the outer shells of the cloud, triggering this to fall onto the disk. Since this matter has a higher specific angular momentum it falls onto the disk at larger radii, where the disk is cooler. This matter therefore will stay amorphous and mix with the crystalline material already in the disk, diluting the crystalline content. The disk becomes more amorphous again. The onset of this dilution with amorphous material is seen in the 3.3×10^5 year curve (dotted curve) in Fig. 2. Dilution continues until infall ceases, which is at slightly less than 1 Myr in this model. Further viscous spreading and radial mixing of the dust will cause the region beyond 10 AU to have an almost constant crystallinity, while in between 1 and 10 AU crystallinity declines with radius, in accordance with the radial mixing theory. The level of the crystallinity in the outer (10-1000 AU) disk region is a heritage from the infall phase set by the amout of cool non-crystallized matter that was able to dilute the crystalline matter from the very early infall phase.

In Fig. 3 we plot the crystallinity at 10 AU at 2 Myr after the onset of collapse for a series of models with different cloud rotation rate Ω. Also shown are the disk masses and accretion rates at 2 Myr.

The figure shows that cloud rotation rates of at least $\Omega \gtrsim 4\times10^{-15}{\rm s}^{-1}$ are required to obtain crystallinity below 30%, which is the approximate upper limit obtained for a sample of Herbig Ae/Be stars by van Boekel et al. (2005). Disks formed from such rapidly rotating clouds are large and require long time to be accreted. At 2 Myr they will still have high disk masses ($M_{\rm disk} \gtrsim 0.4 M_\odot$) and reasonably high accretion rate ($\dot{M} \gtrsim 10^{-7}\,M_\odot$/year).

The crystallinity depends strongly on the detailed treatment of the temperature at the disk midplane. Our standard computation leads to rather hot disks, but many effects might lower the disk temperature, including convection and dust grain growth. The minimum temperature is the effective temperature required to radiate away the energy input from both the irradiation as well as the viscous heating. This lower temperature will evidently yield lower crystallinity. Crystallinity can be suppressed even further by reducing the radial mixing coefficient (i.e. increasing the Prandtl number P_t). The grey curve in Fig. 3 represents models with $P_t = 10$ and minimum temperature. For these models a level of 30% crystallinity can be reached ($M_{\rm disk}$ =0.05 $M_\odot$, $\dot{M} = 10^{-8} M_\odot$/year at 2 Myr).

However, the above assumptions differ drastically from conventional wisdom: The lowest possible estimate of the disk midplane temperature would require a Rosseland optical depth of roughly unity throughout the disk, a rather unlikely coincidence. The real temperature presumably lies somewhere in between the two extremes we tested. The factor of 10 reduction in radial mixing means that the angular momentum in the disk is much more efficiently transported than passive trace elements in the disk. In accretion disk theory the Prandtl number is typically assumed to be about unity.

4. DISCUSSION AND CONCLUSION

In this Letter we have shown that understanding the crystallinity of dust in disks requires the modeling of the entire formation process of the star+disk system, because much of the crystallization occurs in these very early phases. Unlike the existing models in the literature where the initially amorphous disks are gradually enriched with crystals via radial mixing, our model predicts a major heating event and dust crystallization *simulta-*

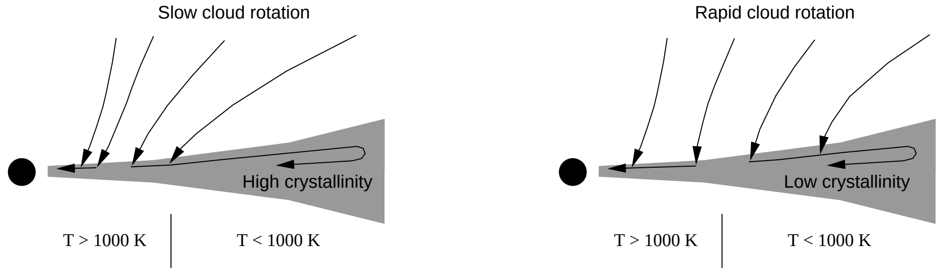

Fig. 4.— Cartoon of how the angular momentum of the infalling matter affects the crystallinity of the resulting disk. Left: low angular momentum infalling matter falls onto the disk within a small region around the star. In this region the disk (in particular in the early active phase) is hot enough to crystallize the dust. Subsequent disk-expansion transports this material outward (some of which later accretes back inward, Lynden-Bell & Pringle 1974). Much (if not most) of the matter observed at large radii originally came from these hot inner regions, and hence has a high abundance of crystalline silicates. Right: high angular momentum matter falls onto the disk at large radii, where the disk is cool. This matter will not get crystallized. Even though radial mixing will pollute it partially with crystalline silicates from smaller radii, the overall crystallinity of the disk will then be much lower than in the high-angular-momentum case.

neously with the build-up of the accretion disk. Thus, in contrast to the gradual increase of crystallinity proposed by others, our model predicts an initially high crystallinity, that possibly may even decrease with time — a prediction that might provide a natural explanation for the probable age–crystallinity anti-correlation indicated by van Boekel et al. (2005) and Apai et al. 2005.

The crystallinity, as well as many other disk parameters measured after the main envelope-infall phase, depends crucially on the angular momentum of the infalling matter: low angular momentum leads to high crystallinity and high angular momentum to low crystallinity. Our model only includes thermal annealing as a crystallization process. Other processes such as shock annealing (both within the disk itself and in the infall-shock on the disk surface) are neglected. Nevertheless, our model typically predicts high levels of crystallinity. A detailed comparison to observations (e.g. to Spitzer IRS spectra and/or VLT-MIDI interferometric spectroscopy data) can therefore put strong constraints on the disk physics. The low levels of crystallinity observed in some sources may require lowering the vertical optical depth of the disk by dust coagulation. We may also be forced to reduce the radial mixing or modify other pieces of basic disk physics. The study of the disk crystallinity, in combination with disk mass and accretion rate, will therefore teach us about several aspects of fundamental disk physics. In upcoming work we will study these aspects in more detail and perform direct comparisons to observations.

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